Lagrangian Studies of Lateral Mixing and an Internal Modeling and Observational Study of Three-Dimensional Upper Ocean Boundary Layer Dynamics and Parameterizations

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LONG-TERM GOALS

I seek to understand the processes controlling lateral mixing in the ocean, particularly at the submesoscale, i.e., 100m-20km.

OBJECTIVES

Existing high-resolution regional models typically resolve the mean vertical structure of the upper ocean boundary layer. Physically-based parameterizations of vertical fluxes make it possible to account for subgrid mixing at length scales smaller than the layer depth, but no specialized parameterization is used to represent the dynamics of horizontal mixing below the O(1)*km* - O(10)*km* resolution scale. We aim to determine the physical limitations of subgrid parameterization on these scales. These projects address the following questions:

- What physics govern horizontal and vertical mixing in the presence of horizontal variability on the 1-10 km scale?
- What is the relative importance of horizontal and vertical mixing in determining the structure of the boundary layer?
- What physics should be included to improve parameterizations?

APPROACH

These projects continue the analysis of the 2006 and 2007 AESOP and fund preparations for the 2011 and 2012 Lateral Mixing experiments. During AESOP, Lee and D'Asaro pioneered an innovative approach to measuring submesoscale structure in strong fronts. An adaptive measurement program employed acoustically-tracked, neutrally-buoyant Lagrangian floats and a towed, undulating profiler to investigate the relative importance of vertical and horizontal mixing in governing boundary layer structure in the presence of O(1 km) scale horizontal variability. Remotely sensed sea surface temperature and ocean color, combined with rapid, high-resolution towed surveys and model results,

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guide float deployments to key locations within fronts. Synoptic, high-resolution surveys followed Lagrangian float drifts to characterize three-dimensional variability within the span of a model grid points. Acoustic tracking allowed towed surveys to follow floats and geo-located all observational assets for later analysis. Measurements characterized boundary layer turbulence and facilitated detailed separation of vertical and horizontal processes. These measurements were specifically designed to allow direct comparison with Large Eddy Simulations of the measurements by Ramsey Harcourt and thus have direct application to assessing regional model subgrid parameterizations.

WORK COMPLETED

The first of two cruises associated with the AESOP effort took place from R/V Roger Revelle, 16 July – 8 August 2006 off the California coast. The best data was taken for 3 days along a north-south front. We call this AESOP I. The second 2007 field effort focused on the strong fronts and submesoscale features associated with the Kuroshio extension. The best data was taken in the region of strong confluence and frontogenesis as the Kuroshio/Oyashio front is formed off Japan. We call this AESOP II.

During 2009, Luc Rainville worked on these projects to redo the analysis of the AESOP II data (see below for results). The analysis of the AESOP II data is thus essentially complete and a manuscript has been written. Submission of this manuscript is awaiting completion of some final details.

Reanalysis of AESOP I is being conducted by Andrey Shcherbina, who starting working on this project in September, 2009. Dr. Shcerbina has begun improving the acoustic tracking of the float and Triaxus and will then recreate the 4-D, space time maps of velocity, temperature and salinity and evaluate the density, velocity, energy and potential vorticity budgets of the approximately 5km square volume of surveyed water. First-cut LES simulations of this case have been completed by Ramsey Harcourt. The intercomparisons await completion of the reanalysis.

Experimental efforts in the Lateral Mixing DRI will continue the work begun during AESOP using similar techniques. Work during 2009 was confined to planning. I participated in planning meetings in December 2008 and June 2009. It has been difficult to reach consensus within the DRI because of the widely different hypotheses held by different participants. I have worked with Leif Thomas, Raf Ferrari and Craig Lee to try to find a single site for two experimental programs, focusing on the Cape Hatteras region.

RESULTS

The reanalysis of the AESOP-II data has focused on a small region of very strong shear and enhanced boundary layer mixing, which we call the "Sharpest Front." This region is remarkable because of the anomalously high turbulence levels and the suggestion that these are due to fluxes of energy from the Kuroshio. As we say in our paper:

> *The mechanisms by which the ocean circulation is dissipated are poorly understood. Here, we present experimental evidence suggesting that significant dissipation occurs at fronts. The confluence of warm subtropical and cold subpolar waters in the Kuroshio extension off Japan formed a front less than a kilometer wide. The turbulence level and energy dissipation rate in the upper boundary layer were 4-7 times larger than in nearby regions. The potential vorticity was*

negative, probably reflecting a wind stress sink, allowing symmetric instability to flux energy from the front, and thus the ocean circulation, to dissipation. Additional dissipation may be due to the radiation of internal waves. Upper ocean boundary layer dissipation could account for a large fraction of dissipation of the large-scale ocean circulation.

The two figures below illustrate these results as explained in the captions.

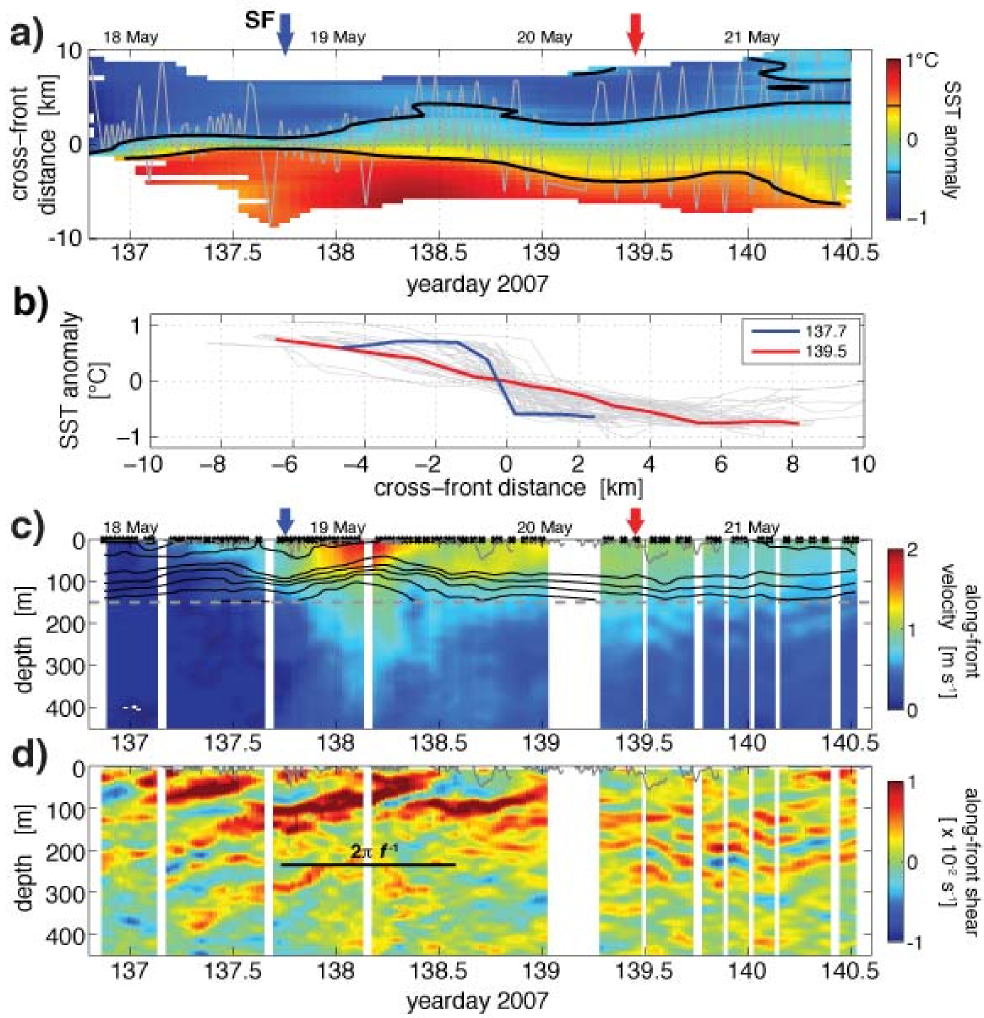

Fig. 1. a) Sea surface temperature deviation (referenced to SST along the front) from ship surveys plotted relative to float position (front). The front is seen to sharpen, becoming the 'sharpest front', only a few hundred meters wide, on day 137.7, and then thicken to several kilometers wide over the next few days. (b) SST as a function of cross-front distance during the whole survey (gray), with the SF and the later reference section highlighted in blue and red, respectively. The same thickening is again seen. (c) Depth-time section of along-front velocity following the float. Potential density is contoured (0.2σ_θ intervals) in the upper 150 m (Triaxus survey range, above dashed gray line). Shipboard ADCP data are used deeper. The sharpest front is seen to coincide with a strong jet in along-front velocity. (d) Vertical shear of east velocity as a function of depth and time along the front. Upward propagating shear features with a near-inertial frequency are seen, with the sharpest front occurring at the location where the strongest of these surfaces.

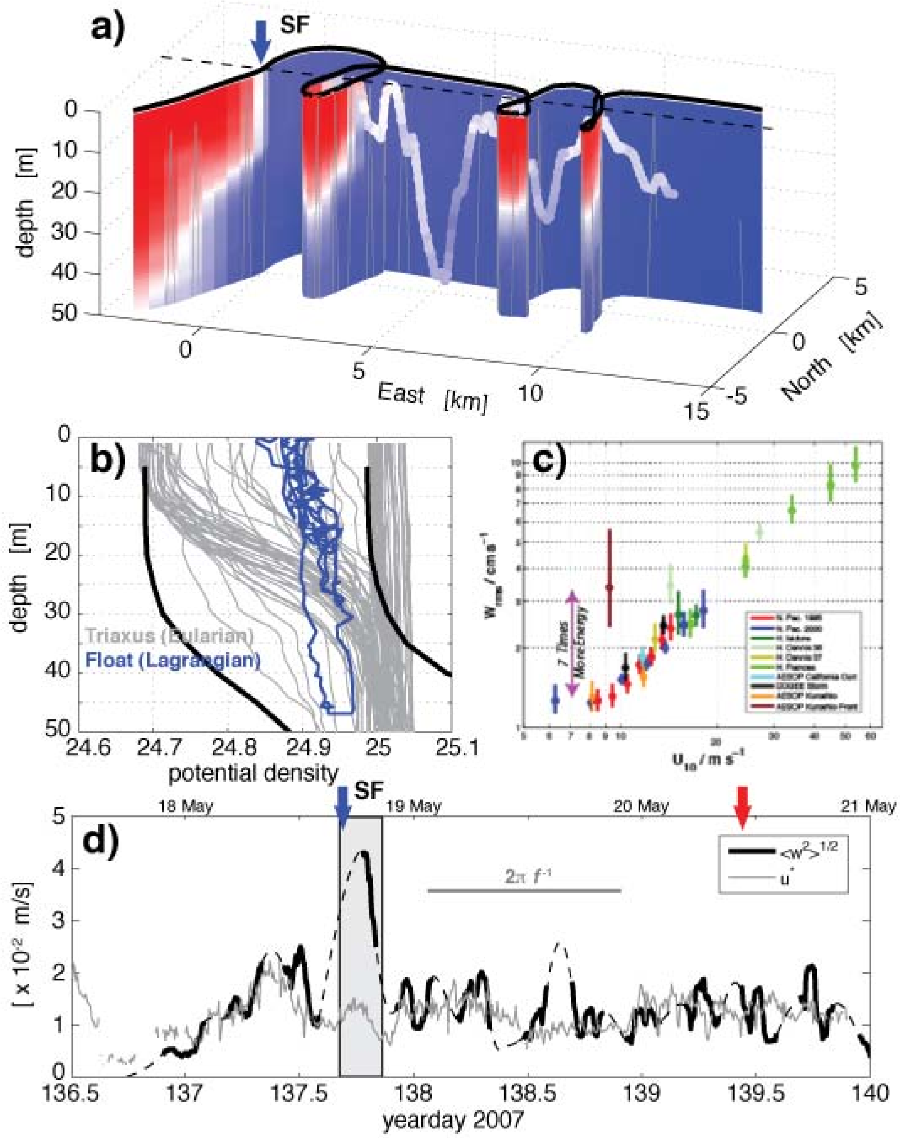

Fig. 2. a) Triaxus and float data around the SF (Sharpest Front). A curtain of Triaxus data is plotted beneath ship track and colored by density. The float trajectory is also colored by density, and its surface projection shown as dashed black line. The float is seen to be travelling along the interface between the warm stratified Kuroshio water to the south and the colder less stratified Oyashio water to the north. b) Density profiles from float (blue) and Triaxus (gray) used in a). Thick black lines are density profiles 4 km north (RHS) and south (LHS) of the front. The float repeatedly moves vertically across the stratified boundary layer, showing that this is an actively turbulent layer. c) Vertical velocity variance from all published float data for wind forced upper ocean boundary layers as a function of wind speed. Confidence intervals are 95%. The vertical velocity variance is an accurate function of wind speed for all data, except for data from SF that lies well above all other data. d) Time series of friction velocity u* (gray) and rms vertical velocity $\boldsymbol{<w^2>^{1/2}}$ ***(thick black line) for the Kuroshio float deployment. Dashed line is a smoothing spline on the float*** $\boldsymbol{<w^2>^{1/2}}$***. The value of*** $\boldsymbol{<w^2>^{1/2}}$ ***for the SF lies well above all other values.***

IMPACT/APPLICATIONS

Our results suggest that a boundary layer parameterization that includes both the effects of atmospheric forcing and lateral gradients is possible and could be implemented in regional models.